Double-Damped Lyman Alpha Absorption: A Possible Large Neutral Hydrogen Gas Filament Near Redshift $z = 1$[1]

David A. Turnshek[2], Sandhya M. Rao[2], Daniel B. Nestor[2],
Daniel Vanden Berk[2], Michèle Belfort[2], and Eric M. Monier[3]

ABSTRACT

We report the discovery of two damped Lyα absorption-line systems (DLAs) near redshift $z = 1$ along a single quasar sightline (Q1727+5302) with neutral hydrogen column densities of $N_{HI} = (1.45 \pm 0.15) \times 10^{21}$ and $(2.60 \pm 0.20) \times 10^{21}$ atoms cm^{-2}. Their sightline velocity difference of 13,000 km s^{-1} corresponds to a proper separation of $106h_{70}^{-1}$ Mpc if interpreted as the Hubble flow ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$). The random probability of such an occurrence is significantly less than 3%. Follow-up spectroscopy reveals neutral gas-phase Zn abundances of [Zn/H] $= -0.58 \pm 0.15$ (26.5% solar) and -1.32 ± 0.28 (4.7% solar), respectively. The corresponding Cr abundances are [Cr/H] $= -1.26 \pm 0.15$ (5.5% solar) and -1.77 ± 0.28 (1.7% solar), respectively, which is evidence for depletion onto grains. Follow-up IR images show the two most likely DLA galaxy candidates to have impact parameters of $\approx 22h_{70}^{-1}$ kpc and $\approx 32h_{70}^{-1}$ kpc if near $z = 1$. They are significantly underluminous relative to the galaxy population at $z = 1$. To investigate the possibility of additional high-N_{HI} absorbers we have searched the SDSS database for $z > 1$ quasars within 30 arcmin of the original sightline. Five were found, and two show strong Mg II-Fe II absorption near $z = 1$, consistent with classical DLA absorption $\approx 37\%$ of the time, but almost always $N_{HI} > 10^{19}$ atoms cm^{-2}. Consequently, this rare configuration of four high-N_{HI} absorbers with a total sightline velocity extent of 30,600 km s^{-1} may represent a large filament-like structure stretching over a proper distance of $241h_{70}^{-1}$ Mpc along our sightline, and a region in space capable of harboring excessive amounts of neutral gas. Future studies of this region of the sky are encouraged.

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[2]Dept. of Physics & Astronomy, University of Pittsburgh, Pittsburgh, PA 15260 (turnshek@pitt.edu, rao@everest.phyast.pitt.edu, dbn@phyast.pitt.edu, danvb@phyast.pitt.edu, mbelfort@phyast.pitt.edu)

[3]Dept. of Astronomy, Ohio State University, Columbus, OH 43210 (monier@astronomy.ohio-state.edu)

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1. Introduction

Intervening damped Lyα absorption-line systems (DLAs) in quasar spectra are very rare, with an incidence of ≈ 0.17 per unit redshift at $z = 1$ (Rao, Turnshek, & Nestor 2004, hereafter RTN2004). Consequently, unless DLAs are correlated, the appearance of two DLAs along any single quasar sightline ("double-damped") represents a very unlikely event. As such, the discovery of any double-damped absorption warrants a closer investigation.

Here we report the discovery of double-damped absorption near $z = 1$ in the Sloan Digital Sky Survey (SDSS) quasar Q1727+5302 during our most recent *Hubble Space Telescope* UV spectroscopic survey for DLAs (RTN2004). The purpose of the present paper is to report initial results pertaining to this discovery, and thereby encourage future studies of this region of the sky. The velocity separation of the absorption is 13,000 km s^{-1}, which corresponds to a proper radial distance of $106h_{70}^{-1}$ Mpc if interpreted as due to the Hubble flow.[1] We speculate that this configuration may represent a neutral hydrogen gas filament with a large cosmological extent along our sightline. In fact, the comoving size of this putative filament would be larger than anything previously reported.

As discussed in earlier contributions (e.g., Rao & Turnshek 2000, hereafter RT2000, and references therein), DLAs are excellent tracers of the bulk of the neutral hydrogen gas in the Universe, and the aim of our most recent DLA UV survey has been to improve our knowledge of the incidence and cosmological mass density of DLAs at redshifts $z < 1.65$. The new sample which led to the discovery of the double-damped absorption was derived from the SDSS Early Data Release (EDR) (Schneider et al. 2002). We applied a strong Mg II-Fe II rest equivalent width (REW) selection criterion (RT2000) to optical spectra in order to identify candidate DLA absorption lines ($N_{HI} \geq 2 \times 10^{20}$ atoms cm^{-2}), and then we obtained HST STIS UV spectra to confirm or refute their presence. The current overall success rate for identifying DLAs with this method is $\approx 37\%$. Since the Mg II$\lambda\lambda$2796,2803 absorption lines are saturated, the REW of the absorption is most closely tied to kinematic spread, not column density. Recently, Nestor et al. (2003) have discussed evidence for a correlation between kinematic spread and metallicity.

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[1]To calculate physical quantities in this paper we adopt a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1} ($h_{70} = H_0/70$).

The paper is organized as follows. In §2 we present the HST discovery spectrum for the double-damped absorption, a follow-up MMT spectrum used to determine neutral-gas-phase metal abundances, and IRTF imaging data used to search for galaxies associated with the double-damped absorbers along the quasar sightline. In §3 we summarize evidence that exists for strong Mg II absorption systems near $z = 1$ in other SDSS quasars in the same region of the sky. A brief summary and discussion of the results is presented in §4.

2. Observations

Q1727+5302 (SDSS J172739.03+530229.16) is the J2000 coordinate designation of the quasar which exhibits double-damped absorption near $z = 1$. The quasar has an emission redshift of $z_{em} = 1.44$ and an SDSS g-band magnitude of 18.3. A search for the Mg II$\lambda\lambda$2796,2803 absorption doublet in bright ($g < 19$) SDSS EDR quasars resulted in the identification of two systems along this sightline at $z = 0.9448$ and $z = 1.0312$. Table 1 gives REWs of some of the identified metal absorption lines.

2.1. Spectroscopy: H I Column Densities and Element Abundances

The spectrum shown in Figure 1 was obtained during a 73 minute exposure with the HST on 1 January 2003 in the STIS NUV G230L mode. See RTN2004 for details of the observing program. The DLA lines at $z = 0.9465$ and $z = 1.0315$ are visible. The insert to the figure shows two Voigt damping profiles that have been fitted simultaneously to the two Lyα lines. These have neutral hydrogen column densities of $N_{HI} = (1.45 \pm 0.15) \times 10^{21}$ atoms cm^{-2} and $N_{HI} = (2.60 \pm 0.20) \times 10^{21}$ atoms cm^{-2}, respectively. The 1σ errors were determined by assessing uncertainties in the continuum fit as described in RT2000.

We used the 6.5-m MMT on 2 July 2003 to obtain spectroscopic observations of both systems making up the double-damped absorption in order to determine their neutral gas phase metal abundances. We used the Zn II and Cr II lines (Figure 2), as well as Si II, Fe II, and Mn II lines (not shown). The method employed to measure the metal abundances is the same as that used by Nestor et al. (2003). Relative to the solar measurements of Grevesse & Sauval (1998), we find Zn abundances of [Zn/H] $= -0.58 \pm 0.15$ (26.5% solar) and -1.32 ± 0.28 (4.7% solar) for the $z = 0.9448$ and $z = 1.0312$ systems, respectively. The corresponding Cr abundances are [Cr/H] $= -1.26 \pm 0.15$ (5.5% solar) and -1.77 ± 0.28 (1.7% solar), so there is evidence for depletion onto grains. These determinations fall within the range of DLA metallicities that have been reported near $z = 1$ (e.g., see Prochaska et al.

2003). Also, for the $z = 0.9448$ system we find [Si/H] $= -0.81 \pm 0.13$ (15.6% solar), [Fe/H] $= -1.37 \pm 0.093$ (4.3% solar)[2], and [Mn/H] $= -1.18 \pm 0.076$ (6.6% solar); for the $z = 1.0312$ system we find [Si/H] $= -1.46 \pm 0.14$ (3.5% solar), [Fe/H] $= -2.10 \pm 0.13$ (0.8% solar)[2], and [Mn/H] $= -1.89 \pm 0.15$ (1.3% solar).

2.2. Infrared Imaging: Luminous Objects Along the Sightline

Some of our recent imaging results on low-redshift DLAs have been reported by Rao et al. (2003). On 2 April 2003 we made similar IR (JHK bands) observations of the double-damped sightline with the 3.0-m IRTF. Figure 3 shows a $14''$ x $14''$ section of the H-band image centered on the quasar. The limiting 1σ surface brightness is 22.0 H magnitudes per square arcsec. Objects labeled G1 and G2 are reasonable candidates for the DLA galaxies based on their proximity to the sightline. If at $z = 1$, their impact parameters of $\approx 2.7''$ and $\approx 4.0''$ correspond to proper transverse distances of $\approx 22h_{70}^{-1}$ kpc and $\approx 32h_{70}^{-1}$ kpc, respectively. G1 and G2 have H-band magnitudes of $m_H(\mathrm{G1}) = 21.1 \pm 0.3$ and $m_H(\mathrm{G2}) = 20.7 \pm 0.2$. They are also visible in our J-band and K-band images (not shown), with magnitudes $m_J(\mathrm{G1}) = 21.5 \pm 0.2$, $m_J(\mathrm{G2}) = 21.7 \pm 0.2$, $m_K(\mathrm{G1}) = 21.0 \pm 0.4$, and $m_K(\mathrm{G2}) = 20.0 \pm 0.2$.

Adopting $L_K^* = -24.1$ from local galaxies studies (e.g., Bell et al. 2003), a k-correction appropriate for an Sa type galaxy from Poggianti (1997), and assuming no evolution, a local L_K^* galaxy redshifted to $z = 1$ would have $m_K = 19.5$ for our adopted cosmology. We note that at $z = 1$ k-corrections for all galaxy types are relatively small in the K-band, and the magnitudes of G1 and G2 would correspond to luminosities of $\approx 0.25 L_K^*(local)$ and $\approx 0.6 L_K^*(local)$, respectively, if they were at $z = 1$. However, recently Ellis & Jones (2004) have presented K-band observations of the galaxy population residing in three x-ray selected massive clusters at $z = 0.8 - 1.0$. Fits to their data indicate that at redshifts near $z = 1$ the galaxy population in massive clusters has K^* lying in the range $17.6 - 18.4$ mag. Thus, $L_K^*(z = 1)$ is $\approx 1.5 \pm 0.4$ mag brighter than $L_K^*(local)$, which is what might be expected from passive evolution. Therefore, G1 and G2 are $\approx 0.06 L_K^*(z = 1)$ and $\approx 0.15 L_K^*(z = 1)$, respectively, and it should be emphasized that there are no good candidate DLA galaxies with luminosities near $L_K^*(z = 1)$. Consequently, if G1 and G2 are passively evolving DLA galaxies, they can simply be interpreted as the progenitors of local dwarfs.

We note that if G1 was at the quasar redshift ($z_{em} = 1.44$), it would be $\approx 0.6 L_K^*(local)$.

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[2]To calculate Fe abundances we used the FeII f-values in the NIST database reported at physics.nist.gov/cgi-bin/AtData/display.ksh in March 2004, whereas for the other elements we used those adopted by Nestor et al. (2003) which were compiled at kingpin.ucsd.edu/∼hiresdla by Jason Prochaska.

However, G1 is offset from the quasar, so if it were related to the quasar it would likely be associated with an interaction. Low-redshift quasar host galaxies are generally several times $L^*(local)$ (e.g., Hamilton, Casertano, & Turnshek 2002; Jahnke & Wisotzki 2003).

3. Search for Strong Mg II in Other SDSS Quasars within 30 arcmin

One way to test the hypothesis that the double-damped absorption represents an extended filament along our sightline is to search for absorption near $z = 1$ in other quasars with $z_{em} > 1$ that lie approximately in the same direction. This possibility can be considered since the SDSS has searched this region of the sky for quasars. Five other $z_{em} > 1$ quasars are known that meet the criteria of having spectra of high enough quality to detect strong Mg II-Fe II systems and lying within 30 arcmin of the double-damped sightline. An angular size of 30 arcmin (SDSS data presently cut off beyond this on one edge) is considerably smaller than the putative $106h_{70}^{-1}$ Mpc (proper distance) long filament at $z = 1$, but this is reasonable if we are viewing cosmic structure along a filament. All five of these other quasars fall below the brightness limits used for inclusion in our current HST UV survey for low-redshift DLAs (RTN2004). Three of the quasars (SDSS Q1727+5301 at $\mathrm{z}_{em} = 1.60$, SDSS Q1727+5306 at $\mathrm{z}_{em} = 1.97$, and SDSS Q1729+5312 at $\mathrm{z}_{em} = 1.33$) do not show evidence for strong Mg II absorption near $z = 1$, so there is little chance that they have DLA absorption near $z = 1$. However, the remaining two do show strong Mg II-Fe II absorption which meet the criterion for selecting DLA candidates (RT2000). The sightline locations and presence of absorption may constrain the geometry of any filament. The two new absorption systems (REWs are reported in Table 1) are at $z = 0.9706$ (in SDSS Q1725+5254 at $z_{em} = 1.36$) and $z = 1.1536$ (in SDSS Q1727+5311 at $z_{em} = 1.80$), separated from the double-damped sightline by ≈ 25 arcmin and ≈ 10 arcmin, respectively. Thus, there are four strong Mg II-Fe II absorption systems that lie along similar sightlines, within a redshift spread of $\Delta z = 0.2088$, corresponding to a velocity separation of $30,600$ km s^{-1}. Given our strong Mg II-Fe II selection criterion, if these new systems are not DLAs, they are almost certainly sub-DLAs with H I column densities $> 10^{19}$ atoms cm^{-2}. Figure 4 shows continuum-normalized regions of the SDSS spectra for all three quasars with strong Mg II-Fe II absorption.

4. Summary and Discussion

Investigations of the possibility of clustering between DLAs and Lyman break galaxies (LBG) have been made at high redshift (e.g., Gawiser et al. 2001, Aldelberger et al. 2003, Bouché & Lowenthal 2003). Gawiser et al. (2001) and Aldelberger et al. (2003) find no

significant evidence for clustering at $z \approx 4$ and $z \approx 3.2$, respectively, while Bouché & Lowenthal (2003) present weak evidence (2.6σ significance) for clustering at $z \approx 3$ on a size scale up to $\approx 1.8 h_{70}^{-1}$ Mpc ($\approx 7 h_{70}^{-1}$ Mpc comoving).

Here we have reported the discovery of an apparently non-random (see below) structure on the sky near redshift $z = 1$ (§2.1) which is much larger than the scales explored in high-redshift DLA-LBG clustering studies and much larger than normal galaxy clustering. The structure consists of two extremely high-N_{HI} (even by DLA standards) DLA absorbers separated by 13,000 km s^{-1} along a single quasar sightline. If interpreted as a cosmological redshift separation, this double-damped structure has a radial proper distance of $106 h_{70}^{-1}$ Mpc. The incidence of DLAs above a survey threshold of $N_{HI} \geq 2 \times 10^{20}$ atoms cm^{-2} is ≈ 0.17 per unit redshift at $z = 1$ (RTN2004). Given this incidence, the probability of observing a second DLA within $\Delta z \approx \pm 0.09$ of another DLA is <3%. We quote this probability as an upper limit because the incidence of DLAs is significantly smaller for higher column density systems, and the column densities of the two systems included in the double-damped absorption are factors of ≈ 7 and ≈ 13 times larger than the survey threshold.[3] Therefore, the double-damped absorption may be the result of correlated DLAs and be caused by a cosmologically extended filament of neutral gas along our sightline.

In addition to the identification of this remarkable structure, we have made metal abundance determinations for the two systems which make up the double-damped absorption. We find them to have [Zn/H] $= -0.58 \pm 0.15$ (26.5% solar) and -1.29 ± 0.27 (4.7% solar), with evidence for some depletion onto grains in both cases (§2.1). Infrared imaging indicates that the two most likely DLA candidate galaxies are relatively faint in relation to the galaxy population at $z = 1$, with K-band luminosities that are $\approx 0.06 L_K^*(z = 1)$ and $\approx 0.15 L_K^*(z = 1)$ (§2.2). These add to the list of underluminous galaxies that have been identified as being responsible for DLA absorption (Rao et al. 2003). The results indicate that the presence of luminous galaxies relative to the local population evidently is not a requirement for the presence of large concentrations of neutral gas. We have also identified two new candidate DLA systems in this same region of the sky, separated from the original sightline by 10 arcmin and 25 arcmin (§3). The discovery of these two additional systems increases the probability that this is a non-random structure. If the two new redshift systems are included, the structure stretches $30,600$ km s^{-1} along the sightline, corresponding to a radial proper distance of $241 h_{70}^{-1}$ Mpc.

Filaments nearly as large as that implied by the double-damped absorption have been

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[3]Of the ≈ 50 DLAs presently known to us at $z < 1.65$, the two which make up the double-damped absorption rank as the 8th and 14th highest N_{HI} systems.

seen in mock redshift surveys and cold dark matter simulations of structure formation. For example, Faltenbacher et al. (2002) report correlations in cluster orientations with respect to one another and find alignments of galaxy clusters' major axes on comoving scales of $\approx 140h_{70}^{-1}$ Mpc, corresponding to a proper distance of $\approx 70h_{70}^{-1}$ Mpc at $z = 1$. The large scale structure simulations of Eisenstein, Loeb, & Turner (1997) show similar alignments.

Recently, Palunas et al. (2004) have reported evidence for a structure with a proper size of $\approx 25h_{70}^{-1}$ Mpc ($\approx 80h_{70}^{-1}$ Mpc comoving), which they found during a search for Lyα-emitting galaxies at $z = 2.38$. Miller et al. (2004) have reported evidence for structures on even larger scales based on an analysis of the QSO distribution in the 2dF redshift survey. For this case of double-damped absorption, the size of the putative neutral hydrogen gas filament would be larger than any claimed so far. Therefore, our interpretation should be considered speculative pending future studies. Nevertheless, the properties of the double-damped absorption are of course relevant to studies of DLAs in general.

The present-day cosmological model (approximately 73% dark energy, 24% dark matter and 5% ordinary matter, e.g., Spergel et al. 2003) is one in which large-scale structures can form early in time. However, a specific set of cosmological parameters may also indicate that it is highly improbable for certain structures to grow from initial Gaussian perturbations. Thus, surveys to find evidence for extreme large-scale structure at high redshift have the potential to result in important cosmological constraints. Based on the numbers of DLAs discovered at low redshift so far and the DLA column density distribution, the existence of this double-damped absorption along one sightline represents evidence for a non-random distribution of DLAs which should be further investigated.

Acknowledgments

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Table 1. Metal Absorption Line Rest Equivalent Width Measurements

Quasar	$z_{\rm em}$	$z_{\rm abs}$	$W_0^{\lambda 2600}$ (Å) Fe II	$W_0^{\lambda 2796}$ (Å) Mg II	$W_0^{\lambda 2803}$ (Å) Mg II	$W_0^{\lambda 2852}$ (Å) Mg I
Q1727+5302	1.44	0.9448	2.19(0.13)	2.83(0.07)	2.51(0.07)	0.99(0.07)
···	···	1.0312	0.76(0.11)	0.92(0.06)	1.18(0.08)	0.33(0.10)
Q1725+5254	1.36	0.9706	0.76(0.13)	1.20(0.12)	1.15(0.12)	···
Q1727+5311	1.81	1.1536	1.26(0.39)	2.32(0.45)	2.38(0.41)	···

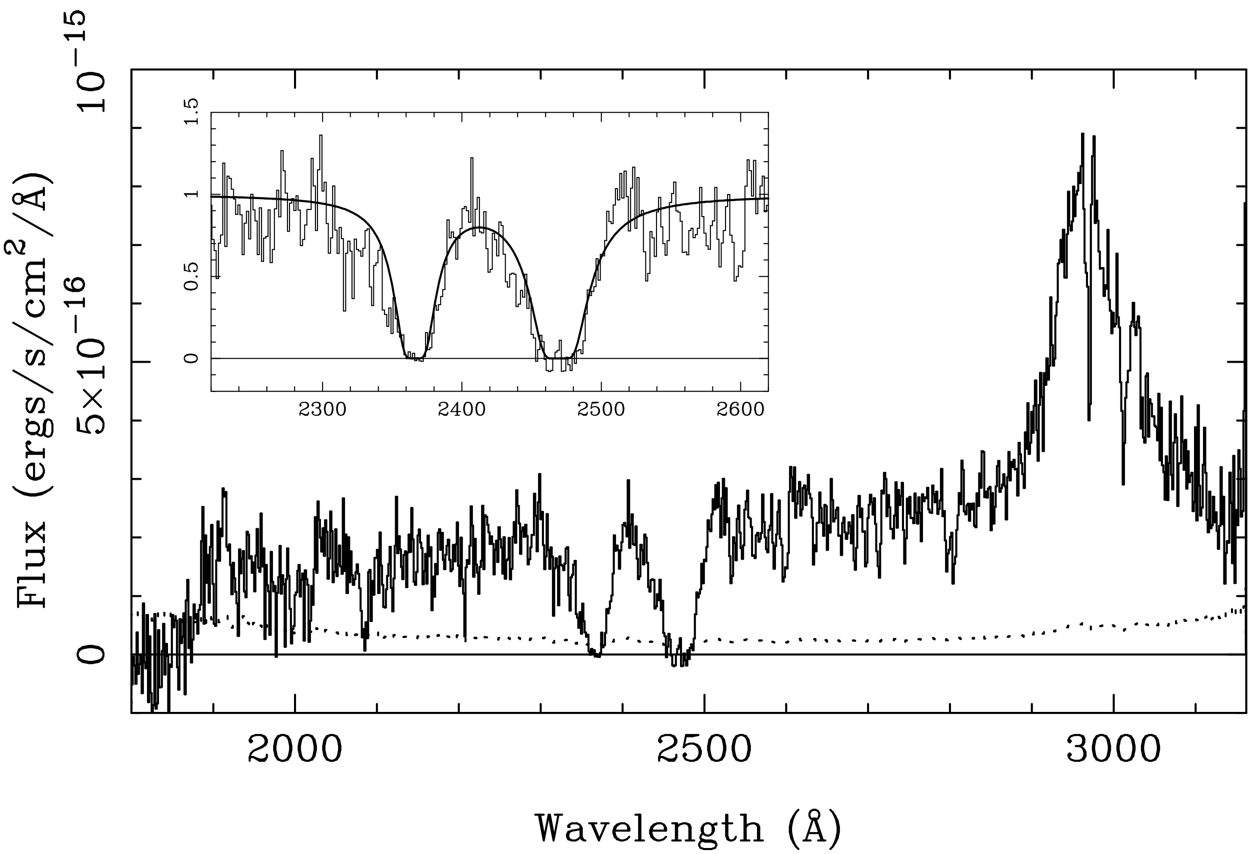

Fig. 1.— HST UV spectrum of the SDSS $z_{em} = 1.44$ quasar Q1727+5302 taken with the STIS NUV/MAMA G230L grating. The quasar's Lyα emission line is at 2966Å and the double-damped Lyα lines are at 2366Å and 2470Å. The dotted line is the 1σ error in flux. The insert shows Voigt profile fits overlaid on the two DLA absorption lines at $z = 0.9465$ and $z = 1.0315$, with H I column densities of $N_{HI} = 1.45 \times 10^{21}$ atoms cm^{-2} and $N_{HI} = 2.60 \times 10^{21}$ atoms cm^{-2}, respectively. The discrepancy between the fitted and observed spectra in the long-wavelength wing of the higher redshift system is probably due to weak Lyβ/OVI emission from the quasar which was not modeled in the fit.

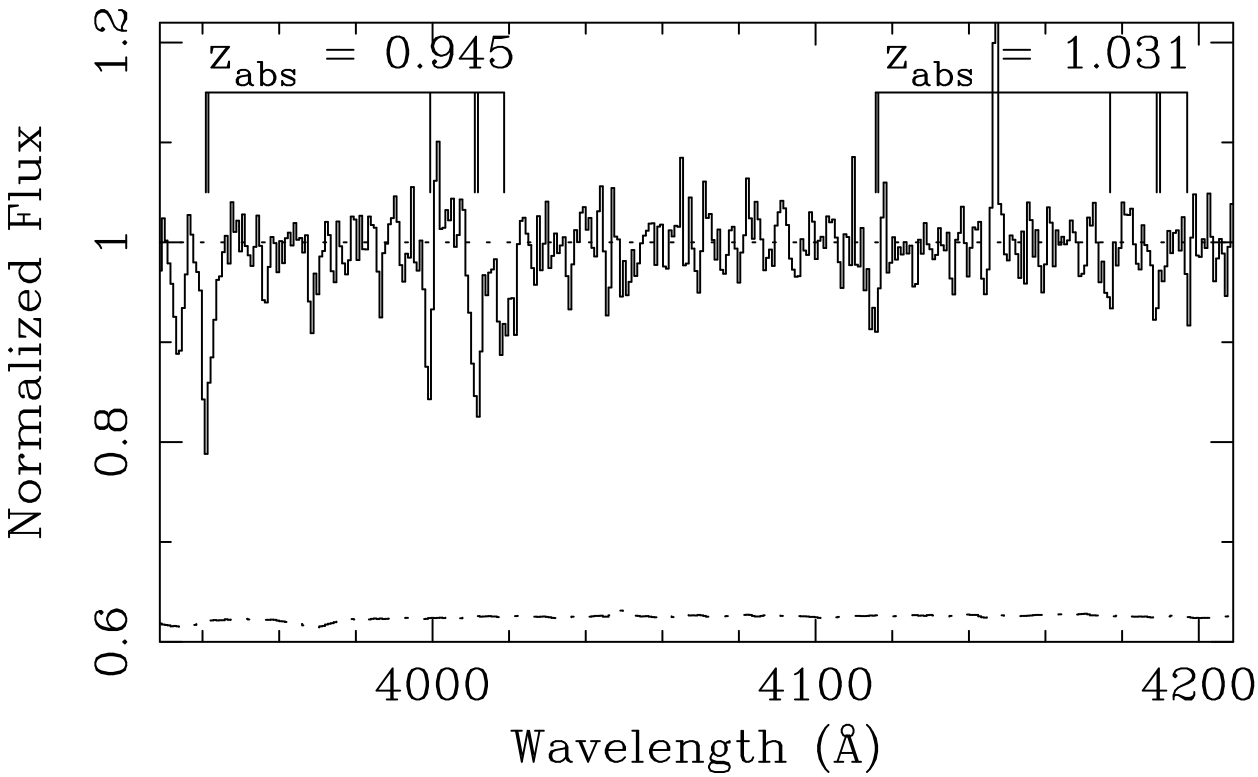

Fig. 2.— MMT spectrum showing the Zn II and Cr II lines in both systems of the double-damped absorption. A discussion about the abundance determinations is given in §2.1. Note that the scale shows only the top part of the normalized spectrum and 0.6 has been added to the error array (dash-dotted line). From left to right the lines labeled in each system are due to Zn II λ2026 (blended with very weak Mg I λ2026), Cr II λ2056, a blend of Zn II λ2062 and Cr II λ2062, and Cr II λ2066.

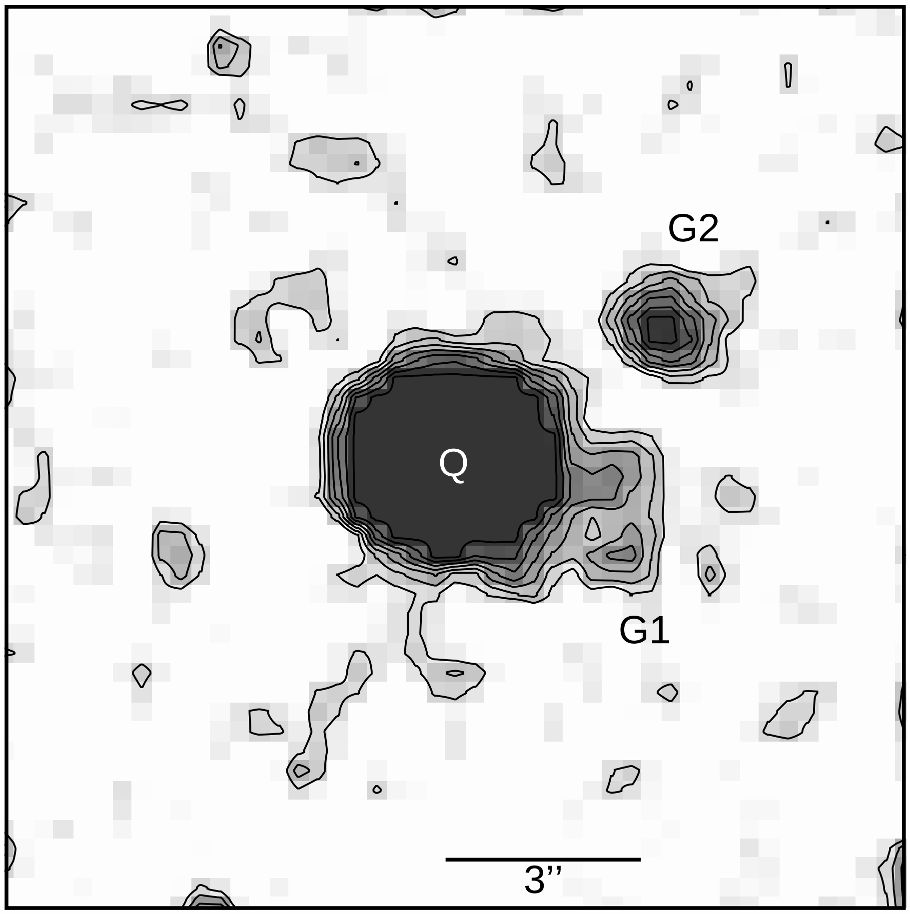

Fig. 3.— Isophotal plot overlaid on an H-band image of the double-damped sightline taken in 1.1 arcsec seeing with the 3.0-m NASA IRTF telescope. It has been smoothed to highlight low surface brightness features, however, measurements were made on the unsmoothed image. The image is $14''$ x $14''$ centered on the quasar (Q). G1 and G2 are the nearest resolved objects with impact parameters of $2.7''$ and $4.0''$. If at $z = 1$, these correspond to proper transverse distances of $22h_{70}^{-1}$ kpc and $32h_{70}^{-1}$ kpc, respectively.

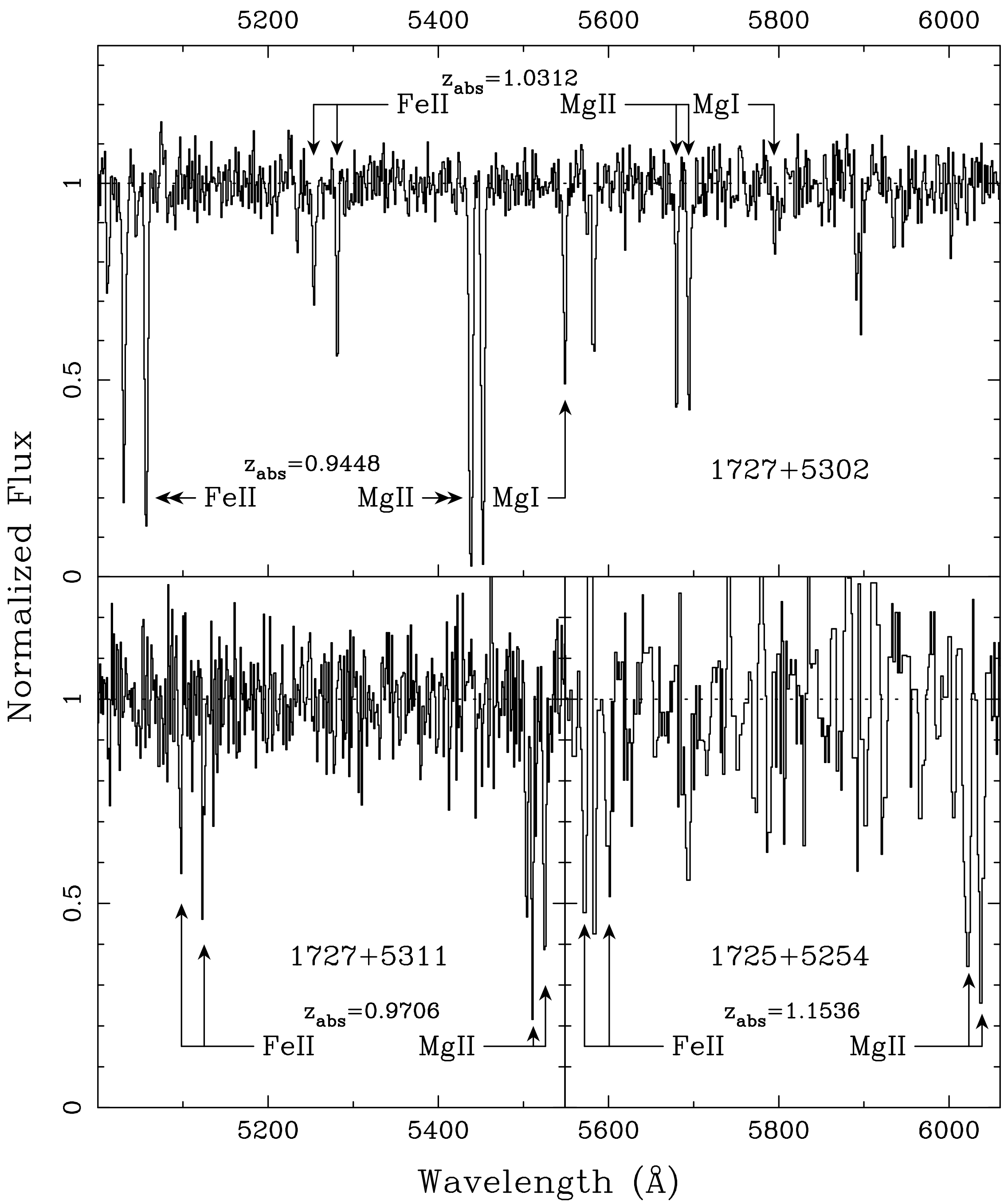

Fig. 4.— Regions of the SDSS spectra for the three quasars which show strong Mg II-Fe II absorption with the continua normalized. The top panel shows the two strong Mg II-Fe II systems that are DLAs in Q1727+5302 at z = 0.9448 and z = 1.0312. The bottom two panels show spectra of two SDSS quasars near the double-damped sightline. The bottom left panel shows the strong Mg II-Fe II system at z = 0.9706 in Q1727+5311. The bottom right panel shows the strong Mg II-Fe II system at z = 1.1536 in Q1725+5254.